Fifty-Nine Reasons for a Supernova to not Explode

M. Liebendörfer

CITA, University of Toronto, Toronto, Ontario M5S 3H8

"We compute the gravitational collapse of cores of massive stars through core-bounce at neutron star densities. In particular we analyze the sensitivity of the results (i.e. the question of whether or not the core bounce gives rise to a supernova explosion of the stellar envelope) with respect to details of the equation of state, neutrino emissivities in the shock region and to properties of the hydrocode. We find that in none of the cases considered is the core-bounce followed by an explosion of the stellar mantle beyond escape velocity. Although a shock always forms, it is never strong enough to accelerate matter to escape velocity. This result is independent of both the details of the equation of state and the assumptions of neutrino losses from the shocked matter". A first glance at this quote does not immediately reveal that it has been written 23 years ago (Hillebrandt & Müller 1981 [1]). One can, however, make out some very clear views. Firstly, the event is appositely called gravitational collapse of massive stars, not supernova explosion. Secondly, only neutrino emissivities in the shock region are mentioned—an adequate focus on the dominant reaction. Thirdly, with visionary marksmanship, shocks are found to *always* form, but *never* lead to explosions. And finally, neutrino *losses* (not absorptions) are scrutinized in the assumptions. But of course, this abstract was written before the suggestion has been made that neutrino heating behind the shock on a time scale of several hundred milliseconds might save the supernova with a delayed explosion mechanism [2]. However, even after the upgrade with the corresponding sophisticated neutrino transport and several input physics improvements, the past five years have still seen an impressive line of supernova models that did not reproduce explosions [3, 4, 5, 6, 7, 8]. Much time has been spent to explain why core collapse supernovae do explode as observed. Here, I review some reasons why they don't.

Reasons 1 & 2

The *electron captures* in the collapse phase stand at the beginning of the causal chain to failed prompt explosions. The condensing material pushes degenerate electrons into increasingly high energy levels from where they are likely to be absorbed on nuclei or free protons. The corresponding neutrino emission leads to deleptonization and the electron fraction decreases, limited only by the neutrino opacity. The latter is dominated by coherent scattering of neutrinos on heavy elements. The thermalization of the trapped neutrinos is important to determine at which neutrino energy the strongly energy-dependent opacities are tapped. The opacities are also affected by ion-ion correlations ([9] and references therein). Fig. 1 compares the entropy and electron fraction evolution in a preliminary simulation with this new liquid structure function to a calculation without ion-ion correlations. The differences are similar to the ones found in previous investigations [10].

After bounce at nuclear density, a pressure wave runs outward through the inner core and turns into a shock at its edge. Because the electron fraction is now low, the causally connected inner core is also small and the shock has to dissociate all material external to its edge. Within 5 ms after bounce, all kinetic energy of the shock is consumed in *nuclear dissociation* and the shock turns into a pure accretion front. Supernova modellers desperately reduced the mass

of the progenitor stars (25 $M_\odot$ [1], 15 $M_\odot$ [4], 13 $M_\odot$ [6], 11 $M_\odot$ [7]), but the survival of the prompt hydrodynamic bounce-shock can even be excluded in the collapse simulation of a 9 $M_\odot$ ONeMg core (Fig. 2a). Moreover, each recent improvement in collapse physics made the situation worse: An upper limit to the enclosed mass is given by a self-regulation mechanism in the electron capture on free protons [11]. The consideration of general relativistic dynamics shifts the enclosed mass further inward by 0.1 $M_\odot$ [6], and improved electron capture rates on heavy nuclei subtract another 0.1 $M_\odot$ [12, 13].

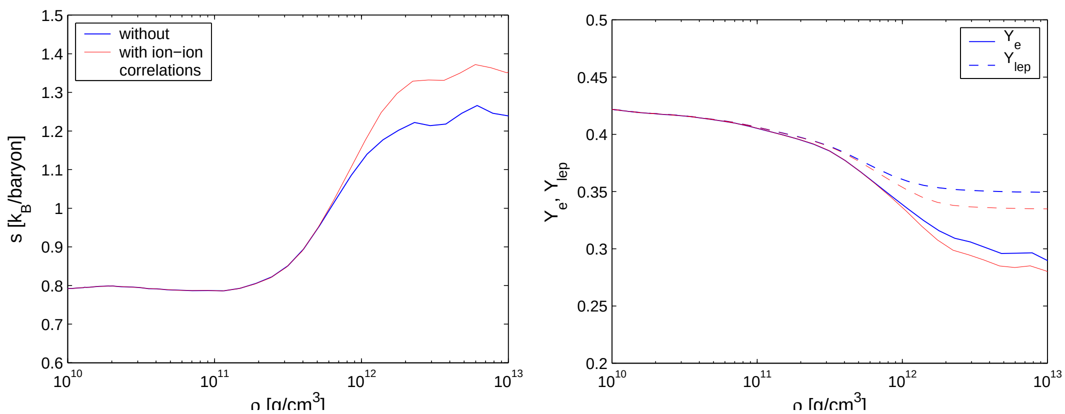

Figure 1: Above simulations with Agile-Boltztran [14] compare the entropy and electron/lepton fraction in a simulation with ion-ion correlations [9] to a simulation without ion-ion correlations. As expected, the former lead to higher entropies and lower electron/lepton fractions. More detailed comparisons between different implementations of liquid structure functions remain to be made.

Reasons 3 & 4

Whenever kinetic energy is left in the shock at 5 ms after bounce, an energetic neutrino burst will definitely zap it away at that time. Namely, as soon as the shock heats material at neutrino-transparent densities, *neutrino cooling* by electron and positron capture on free nucleons starts to determine the action. The accretion front is still expanding its radius because of the accumulation of shock-heated material on the protoneutron star. But before $\sim$ 50 ms after bounce no neutrino heating is possible, because the dissipated kinetic energy at the accretion front propels the matter already to higher entropies than equilibrium in the neutrino background field. Only later, when the accretion front bounds the accumulated hot matter at a larger radius (not as deep in the gravitational potential) and when the neutrino spectra at the receding neutrinospheres have become harder (deeper in the gravitational potential), the entropy after shock passage is lower than equilibrium. At this time, infalling matter is neutrino-heated until it joins the equilibrium entropy at the gain radius [14]. The delicate balance between cooling and contraction at the surface of the protoneutron star and heating behind the accretion front has been analyzed in stationary [15] and dynamic [16] analytical investigations. In (Janka 2001 [16]) we read "It must be suspected that excessive neutrino emission in the cooling layer, causing mass and energy loss from the gain layer, may have been the main reason why spherically symmetric simulations ultimately failed to produce explosions."

This is clearly illustrated in a time-dependent analysis of the massflux through the heating and cooling region in the supernova simulations of Ref. [6], Fig. 7e-h. Deleptonization at the base of the cooling layers draws matter at a very *high accretion velocity* (twice as high in general relativistic simulations [5]) through the heating region such that the effective heating is small. This pessimistic view neglects that the competition between heating and cooling is positively influenced by convection in the heating region. In a convective environment, part of the energy loss by neutrino emission can be avoided by the more adiabatic expansion of local outflows [17].

Reasons 5 & 5.9

"It is important to note that one is not obliged to unbind the inner core ... as well; the explosion is a phenomenon of the outer mantle at ten times the radius ($50-200$ kilometers)" (Burrows & Thompson 2002 [18]). Indeed, e.g. at 200 ms after bounce, more than 1.25 $M_\odot$ have been accreted, and for not too massive progenitors, the accretion rate has decreased to a fraction of a solar mass per second [14]. The nature of a supernova explosion might more suitably be characterized as a surface effect on a nascent compact object than as a dynamical consequence of core collapse. The latter is separated from the explosion by an unspectacular accretion phase. The different relevance of input physics divides these two events as well. Collapse relies on neutron-rich heavy nuclei under electron-degenerate conditions, the supernova rather involves the dynamics of dissociated nucleons in the hot mantle. At that time, many details of the collapse history are buried within the innermost solar mass and, together with some uncertainties in the high density input physics, hidden behind the neutrinospheres (the opacities at $\sim 10^{12}$ g/cm^3 are thought to be well-understood). One has to be careful, though, because this view crucially depends on the *convective stability of the protoneutron star* made out in the most sophisticated non-exploding supernova models [8]. Many explosive models relied on [19] or showed [17] vigorous protoneutron star convection. A careful investigation of this issue is very important [20].

Reason 5.9, finally, is not a real reason and therefore gets a lesser weight: *Technical difficulties* in the supernova models could also be responsible for some of the problems. The outcome of supernova simulations depends quite sensitively on details of the input physics and its numerical treatment. But from the computational point of view, it is extremely expensive to guarantee the accuracy of the neutrino transport. On the other hand, confronted with three-dimensional cosmological MHD simulations that resolve 1400 zones cubed [21], one cannot avoid thinking that it would be exciting to have a similar 3D look at a convective heating region, notabene with a resolution of a fluid element per pixel on the laptop screen. In current supernova simulations that solve the Boltzmann equation for the neutrino transport, negligible time is spent on hydrodynamics. Most additional information per invested computation time can be gained if the dimensionality of the hydrodynamics is increased until it consumes about half of the computational load. A code under development at CITA aims to enhance multidimensional hydrodynamics with a neutrino leakage scheme to locally update a spherically averaged neutrino background field in a perturbative approach. The goal is a hydrodynamically well-resolved (but neutrino-approximative) alternative for the study of the heating region, which, by choice of numerical methods, is as orthogonal as possible to the existing three-dimensional simulations in Ref. [22]. Fig. 2b shows the velocity profile in an exploratory three-dimensional test-simulation of core collapse with an equidistant resolution of 1 km. It uses the Lattimer-Swesty equation of state and a phenomenologically parameter-

ized deleptonization in place of the not yet implemented neutrino physics. A decomposition of the velocity field according to [23] has been extended such that the entropy equation is solved for the smooth bulk velocity component and the total energy equation is solved for the peculiar velocity component. The purpous is to keep the condition of the fast infalling cool matter stable on the Eulerian grid while still correctly dissipating local turbulence and discontinuities into thermal energy.

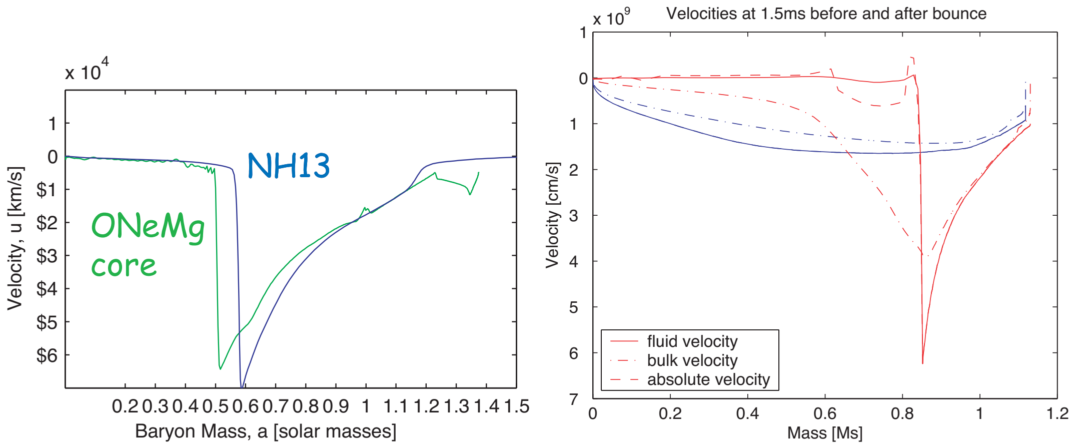

Figure 2: Both graphs show velocity profiles as a function of enclosed mass. The simulation on the left hand side with Agile-Boltztran [14] has been launched from a 13 $M_\odot$ star (NH13) and from a 9 $M_\odot$ ONeMg core [24]. In the ONeMg core, the shock forms even deeper than in the NH13 core, a prompt explosion is therefore not possible. The simulation on the right hand side shows the spherically averaged velocity profile of a 3D test-simulation based on an extended code version of [21] in two time slices around bounce. The smooth bulk velocity (dash-dotted line) and total velocity (solid line) are distinguishable. Convection becomes visible in the large absolute velocities (dashed line) behind the shock. Adequate neutrino physics remains to be implemented.

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